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VENTILATED CAVITY TEST OF A 3-INCH DIAMETER STREAMLINED NOSE

J. W. Holl, D. R. Stinebring and W. R. Hall

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A ventilated cavity test of a 3-inch diameter streamlined nose has been conducted in the 48-inch water tunnel. Tests were conducted at 10, 20, 30 and 40 fps for dimensionless cavity lengths (L_C/D) from approximately 1 to 4. The cavitating flow was documented by video tape and still photography. The purpose of the test was threefold namely (1) to approximate the ventilation flow rate coefficient (C_Q) (2) to observe the stability of the pressure over

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control system as gas was added to the flow, and (3) to observe the approximate boundary between the twin vortex regime and reentrant jet regime. The major results are (1) the ventilation flow rate coefficient is approximately 30% greater than that estimated for a quarter caliber ogive nose, (2) the pressure control system is stable and (3) the twin vortex regime is primarily confined to velocities of 10 fps and less for the gas flow rates employed in this investigation.

Subject: Ventilated Cavity Test of a 3-inch Diameter Streamlined Nose

References: See page 17

Abstract: A ventilated cavity test of a 3-inch diameter streamlined nose has been conducted in the 48-inch water tunnel. Tests were conducted at 10, 20, 30, and 40 fps for dimensionless cavity lengths (L_C/D) from approximately 1 to 4. The cavitating flow was documented by video tape and still photography. The purpose of the test was threefold namely (1) to approximate the ventilation flow rate coefficient ($C_{\dot{Q}}$) (2) to observe the stability of the pressure control system as gas was added to the flow, and (3) to observe the approximate boundary between the twin vortex regime and reentrant jet regime. The major results are (1) the ventilation flow rate coefficient is approximately 30% greater than that estimated for a quarter caliber ogive nose, (2) the pressure control system is stable and (3) the twin vortex regime is primarily confined to velocities of 10 fps and less for the gas flow rates employed in this investigation.

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C_D	Drag coefficient
$C_{\dot{Q}}$	Ventilation flow rate coefficient (Eq. 1)
D	Maximum diameter of the body
F	Froude number (Eq. 7)
g	Gravitational acceleration
L_B	Body length
L_C	Cavity length
n	Number of measured values (Eq. 17)
P_C	Cavity pressure (Eq. 13)
P_G	Noncondensable gas pressure in the cavity
P_{G-S}	Gas pressure at saturation
P_V	Vapor pressure
P_∞	Pressure at infinity
$\dot{Q}$	Volume flow rate of the ventilation air
$\bar{\dot{Q}}$	Average value of $\dot{Q}_i$ (Eq. 17)
$\dot{Q}_i$	The i^{th} value of $\dot{Q}$ (Eq. 17)
$\dot{Q}_D$	Diffused gas flow rate (Eq. 2)
$\dot{Q}_T$	Total gas flow rate (Eq. 2)
R	Reynolds number (Eq. 7)
s	Standard deviation (Eq. 17)
S	Relative standard deviation (Eq. 18)
V_∞	Velocity at infinity
α	Dissolved gas content (Eq. 6)
β	Henry's law constant (Eq. 6)

ν	Kinematic viscosity of the liquid
ρ	Mass density of the liquid
σ_c	Cavitation number based on cavity pressure (Eq. 10)
σ_v	Cavitation number based on vapor pressure (Eq. 12)

Subscripts

QCO	Quarter caliber ogive
SN	Streamlined nose

I. INTRODUCTION

For several years the Applied Research Laboratory (ARL) has conducted a research program on the cavity running phase of the water entry phenomenon. This program is in support of water entry studies at the Naval Surface Weapons Center (NSWC). The ARL contributions to this program are concerned with the following two basic problems:

1. When will the entry cavity disappear or become small enough so that the control surfaces and propulsor can be actuated?

2. How does the drag coefficient (C_D) vary with the cavity length-to-body length ratio (L_C/L_B)?

The tests described in this report are relevant to both problems but were primarily conducted to determine a solution of the second problem.

II. DESCRIPTION OF THE TESTS

2.1 Objectives

In pursuit of an answer to the C_D versus L_C/L_B question indicated in section I, ARL plans to conduct a ventilated drag study of a 3-inch diameter cylindrical body with a streamlined nose. Prior to this study it will be necessary to design a drag balance. In view of uncertanties associated with such a design and with conducting tests in the 48-inch water tunnel with large amounts of gas emission it was desirable to conduct a preliminary ventilated cavity flow test with the streamlined nose alone.

The objectives of the test program were threefold:

(1) To approximate the ventilation flow rate coefficient ($C_{\dot{Q}}$) in order to estimate the ventilation flow rate ($\dot{Q}$) for various velocities and cavity lengths (L_C).

(2) To observe the stability of the pressure control system as gas is added to the flow.

(3) To observe the approximate boundary between the twin vortex regime and reentrant jet regime.

2.2 Test Procedures

An initial test was conducted utilizing a three-inch diameter streamlined nose positioned approximately four inches upstream of the vertical support pipe as shown in Figure 1A. This configuration caused significant disturbance to the cavity flow, with a cavity forming in the wake behind the vertical support pipe. To help alleviate the problem a fairing was constructed about the vertical support as shown in Figure 1B. In addition, shortening the horizontal support further reduced disturbances at the downstream portion of the cavity where most of the entrainment occurs.

The system designed for the introduction of the ventilation air is shown in Figure 2. There were two flowmeters connected in parallel that could be used either independently or together. A pressure gage was located just after the flowmeters for measurement of the ventilation air pressure.

A total of 30 runs were made in the 48-inch water tunnel at velocities from 10 to 40 fps and the basic data are tabulated in Table 1. The maximum ventilation air flowrate for the tests was 9.64 scfps*. The test procedure was as follows:

1. The tunnel velocity and static pressure were first set for the test conditions.

2. The ventilation air was then adjusted for the desired cavity length while a video tape system recorded the cavity behavior. Larger ventilation flow rates required both flowmeters 1 and 2 to be used in parallel. For smaller flowrates flowmeter number 2 was used alone.

3. The freestream velocity, static pressure, flowmeter readings, flowmeter pressure, and cavity length were recorded during the test

Graduated rulers were taped to the windows on both sides of the test section. By sighting across the test section and aligning the two rulers the cavity length could be determined. The cavity length was also measured from the images recorded by the video tape system. Photographs of the cavity were taken with both a stroboscopic flash and continuous lighting during runs 20 through 30.

Several difficulties were encountered with the gas emission and flow rate measurement systems. Recommendations to improve this system are given in Section IV.

*scfpm= standard cubic feet per minute i. e. cfpm at 14.7 psia.

III. TEST RESULTS

3.1 Ventilation Flow Rate Coefficient

The primary concern in this section is to present the ventilation flow rate data for the streamlined nose and to compare it with similar data for other headforms.

It is convenient to express the ventilation flow rate ($\dot{Q}$) in dimensionless form; namely, the ventilation flow rate coefficient ($C_{\dot{Q}}$) given by

$$C_{\dot{Q}} = \frac{\dot{Q}}{V_\infty D^2} \tag{1}$$

where V_∞ and D are the velocity at infinity and maximum body diameter, respectively. Flow rate data have been determined at ARL for a variety of headforms namely quarter-caliber ogives [1]*-[3], zero caliber ogives [1]-[3] and conical nosed bodies [4].

For a given flow state the total flow of gas ($\dot{Q}_T$) entrained at the trailing edge of the cavity is given by

$$\dot{Q}_T = \dot{Q} \pm \dot{Q}_D \tag{2}$$

where $\dot{Q}$ and $\dot{Q}_D$ are the ventilated gas flow rate and diffused gas flow rate, respectively. Thus in order to determine the total gas flow rate ($\dot{Q}_T$) it is necessary to know both $\dot{Q}$ and $\dot{Q}_D$. The flow rate $\dot{Q}$ can be measured directly but $\dot{Q}_D$ is difficult to determine although Billet and Weir [1] [2] *have been reasonably successful in calculating its value by means* of a diffusion theory developed by Brennen [5]. Hence in order to determine $\dot{Q}_T$ in the most direct manner it is prudent to conduct the test so that

$$\dot{Q}_D = 0 \tag{3}$$

and hence

$$\dot{Q}_T = \dot{Q} \tag{4}$$

In principle Equation (3) can be satisfied if the cavity pressure (P_C) is constant along the cavity and if it is set equal to the gas pressure at saturation (P_{G-S}) that is

$$P_C = P_{G-S} \tag{5}$$

* Number in brackets refer to documents in list of references.

where P_{G-S} is given by Henry's Law

$$P_{G-S} = \alpha\beta \qquad (6)$$

in which α is the dissolved gas content and β is the Henry's Law constant. However, Equation (3) can only be approximately satisfied since the pressure does vary somewhat along the cavity. Nevertheless, Billet and Weir [1] [2] have shown that the aforementioned test procedure works satisfactorily and has been employed to find $C_{\dot{Q}}$ for ogives [1] - [3] and cones [4].

The intent of the $\dot{Q}$ tests for the streamlined nose was to obtain sufficient data in order to estimate the volume flow rate characteristics of the nose over a range of flow states for the drag studies to be conducted in the future. Thus, the aformentioned test procedure which was employed with the ogives and cones was not utilized with the streamlined nose since it is very time consuming and in any case $\dot{Q}_D$ is significantly smaller than $\dot{Q}$. Instead the $\dot{Q}$ data for the streamlined nose were obtained by setting the tunnel pressure at a convenient level for each run and then estimating the cavity pressure by a procedure which will be described subsequently.

The $C_{\dot{Q}}$ data for the ogives and cones have been correlated with an equation of the form

$$C_{\dot{Q}} = C\, R^a\, F^b\, (L_c/D)^c \qquad (7)$$

where R = Reynolds number = $\frac{V_\infty D}{\nu}$

F = Froude number = $\frac{V_\infty}{\sqrt{g\,D}}$

a, b, c, D are constants for a given configuration

Of the three models previously tested at ARL the quarter caliber ogive (QCO) can be expected to be the best approximation of the streamlined nose and will thus be employed as a basis for comparison. The correlation for the QCO [3] is

$$C_{\dot{Q}-QCO} = 0.32\text{x}\ 10^{-4}\ R^{0.46}\ F^{0.26}\ (L_C/D)^{0.74} \qquad (8)$$

and the relation between σ_c and L_C/D for the QCO [6] is given by

$$\sigma_c = 0.460\ (L_C/D)^{-0.66} \qquad (9)$$

in which σ_c is the cavitation number based on cavity pressure (P_C) given by

$$\sigma_c \equiv \frac{P_\infty - P_C}{\frac{1}{2}\rho V_\infty^2}\ . \qquad (10)$$

The values of $C_{\dot{Q}}$ and $\dot{Q}$ for the QCO caluclated by means of Equation (8) for a 3-inch diameter nose for velocities from 10fps to 60fps and for values of L_C/D from 1 to 12 are tabulated in Table 2. The $\dot{Q}$ data of Table 2 are plotted in Figure 3. All values of $\dot{Q}$ correspond to the cavity pressure (P_C).

In order to compare the measured streamlined nose data with that of the QCO it is necessary to correct the measured values of $\dot{Q}$ at one-atmosphere to cavity pressure. It is thus necessary to estimate P_C for the streamlined nose since it was not measured. Analysis of data for a nose which is quite similar to that of the test nose indicates that

$$\sigma_v = 0.456 \; (L_C/D)^{-0.292} \tag{11}$$

where σ_v is the cavitation number based on vapor pressure given by

$$\sigma_v \equiv \frac{P_\infty - P_V}{\frac{1}{2}\rho V_\infty^2} \tag{12}$$

Since the cavity pressure is given by

$$P_C = P_G + P_V \tag{13}$$

where P_G and P_V are the noncondensable gas pressure and vapor pressure, respectively it follows that

$$\sigma_c < \sigma_v \quad . \tag{14}$$

We thus need an estimate of the relationship between σ_c and σ_v. To obtain this estimate we employ some plano-convex hydrofoil data of Wade and Acosta [7] plotted in Figure 4. It is seen that these data are approximated by the relation

$$\sigma_c = 0.8333 \; \sigma_v \quad . \tag{15}$$

The measured values of $\dot{Q}$ at 14.7 psia for the streamlined nose were corrected to cavity pressure by employing Equations (10), (11) and (15) and the calculations are tabulated in Table 3. The runs of major interest are those corresponding to the reentrant jet regime. Excluding twin vortex regime data (Run #5) and Runs #1 and #10 because of strut interference and averaging the remaining runs indicates that

$$\bar{\dot{Q}}_{SN} = 1.3 \; \bar{\dot{Q}}_{QCO} \quad . \tag{16}$$

The standard deviation (s) is defined as

$$s = \sqrt{\frac{\sum_{i=1}^{n} (\dot{Q}_i - \overline{\dot{Q}})^2}{n - 1}} \quad . \tag{17}$$

See for example page 198-199 of Reference [8] for the definition of s. The relative standard deviation in percent (S) is defined as

$$S \equiv \frac{s}{\overline{\dot{Q}}} \times 100 \quad . \tag{18}$$

S was calculated and found to be 46.5% which indicates a rather broad variation in the data about the mean. This is perhaps not surprising considering that the effects of $\dot{Q}_D$ were ignored, that σ_c was estimated and that L_C/D is basically an inaccurate measurement.

Applying Equation (16) to Equation (8) yields the estimate

$$C_{\dot{Q}-SN} = 0.42 \times 10^{-4} R^{0.46} F^{0.26} (L_C/D)^{0.74} \quad . \tag{19}$$

Equation (19) together with the data in Table 3 provide sufficient information for estimating Q for the streamlined nose.

3.2 Stability of the Water Tunnel Pressure Control System

The emission of gas into the water can influence the control of the pressure level. It is of course necessary to be able to control the pressure during a ventilated cavity test and it was therefore important to observe the stability of the water tunnel pressure control system during the gas emission tests. In general, it can be stated that the pressure control system was very stable over the entire range of test conditions displayed by the test data in Table 1. No instabilities were observed over the time spans investigated, one of which was over two minutes at 9.4 scfpm. For all cases, the time spans were significantly greater than that necessary to obtain force measurements.

3.3 Flow Regimes - Reentrant Jet and Twin Vortex

The trailing edge region of a cavity flow produced by vaporous cavitation is characterized by the so-called reentrant jet. However, ventilated cavity flows are characterized by two flow regimes; namely, the reentrant jet and twin vortex [9]. The twin vortex regime can occur for a ventilated cavity flow if the gravitational force vector is not parallel to the direction of motion.

Both flow regimes were observed during the ventilated cavity flow test with the streamlined nose and photographs of typical examples of the reentrant jet and twin vortex flow regimes are shown in Figures 5 and 6. In general, for the gas flow rates employed in this test program, the twin vortex regime occured at velocities of 10 fps and less.

IV RECOMMENDATIONS

It is suggested that the final model design be statically tested before installation in the 48-inch water tunnel. In this way, the entire system including the flowmeter assembly and all interconnecting plumbing could be checked out for the flow rates required during water tunnel testing.

One problem with the present model design is the possibility of choked flow at the ventilation holes. A model configuration which will remedy this problem is shown in Figure 7. The ventilation air is directed through a slot between an adjustable nose and the afterbody. The aft section of the nose is threaded where it joins the afterbody. The slot width can be varied by screwing the nose section in or out. Thus, the maximum ventilation flow rate through the slot can be varied quite easily.

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TABLE 1 TABULATION OF BASIC DATA FOR VENTILATED CAVITY
TEST OF 3-INCH DIAMETER STREAMLINED NOSE (SN)
(P_A = 14.05 PSIA, Water Temperature = 68°F)

Run Number	V_∞ FPS	P_∞ PSIA	$\dot{Q}_1$ at P_A CFPM	$\dot{Q}_2$ at P_A CFPM	$\dot{Q}$ at P_A CFPM	$\dot{Q}$ at P_{A-S} CFPM	P_F PSIA	L_C/D	Regime
1*	30	13.8	—	3.31	3.31	3.16	18.75	1.4-3.4	RJ
2	30	13.8	3.85	2.03	5.88	5.62	29.45	3.1	RJ
3	30	13.9	5.75	2.49	8.24	7.88	38.45	3.7	RJ
4	30	13.9	9.55	—	9.55	9.13	45.25	4.1	RJ
5	10	13.7	—	3.69	3.69	3.53	20.55	4.0	TV
6	10	13.8	—	1.00	1.00	0.96	14.35	2.3	RJ
7	10	13.8	—	2.16	2.16	2.06	16.25	3.1	RJ
8	10	13.8	—	2.67	2.67	2.55	17.45	3.4	RJ
9	10	13.7	—	—	—	—	—	—	—
10*	20	13.7	—	2.42	2.42	2.31	16.55	1.7-2.9	RJ
11	20	13.8	4.40	2.58	6.98	6.67	33.15	3.4	RJ
12	20	13.8	9.75	—	9.75	9.32	46.45	4.3	RJ
13	40	18.0	8.95	—	8.95	8.55	44.45	3.1	RJ
14	40	18.0	9.80	—	9.80	9.37	47.65	3.4	RJ
15	40	18.2	10.09	—	10.09	9.64	48.65	3.7	RJ
16 - 30	Photographic Data Only								

V_∞ = Velocity in test section at ∞

P_∞ = Pressure in test section at ∞

$\dot{Q}_1$ = Volume flow rate as measured by meter #1

$\dot{Q}_2$ = Volume flow rate as measured by meter #2

$\dot{Q} = \dot{Q}_1 + \dot{Q}_2$

P_A = Local atmospheric pressure = 14.05 psia

P_{A-S} = Standard atmospheric pressure = 14.7 psia

P_F = Pressure at flow meter

L_C = Cavity length measured from video tape

D = Maximum body diameter

RJ = Reentrant jet

TV = Twin vortex

*Strut interference

TABLE 2 CALCULATED VALUES OF $C_{\dot{Q}}$ AND $\dot{Q}^*$ - QUARTER CALIBER OGIVE (D = 3 inches)

$$C_Q = 0.32\times10^{-4}\ R^{0.46}\ F^{0.26}\ (L/D)^{0.74}\ ;\quad \sigma_c = 0.460\ (L/D)^{-0.66}$$

L_C/D	10FPS $C_{\dot{Q}}$	10FPS $\dot{Q}$	20FPS $C_{\dot{Q}}$	20FPS $\dot{Q}$	30FPS $C_{\dot{Q}}$	30FPS $\dot{Q}$	40FPS $C_{\dot{Q}}$	40FPS $\dot{Q}$	50FPS $C_{\dot{Q}}$	50FPS $\dot{Q}$	60FPS $C_{\dot{Q}}$	60FPS $\dot{Q}$
1	0.0135	0.506	0.0225	1.688	0.0298	3.353	0.0366	5.490	0.0430	8.036	0.0491	11.048
2	0.0225	0.844	0.0376	2.820	0.0497	5.591	0.0612	9.180	0.0719	13.481	0.0819	18.428
3	0.0304	1.140	0.0507	3.803	0.0671	7.549	0.0826	12.390	0.0970	18.188	0.1106	24.885
4	0.0377	1.414	0.0628	4.710	0.0831	9.349	0.1022	15.330	0.1200	22.500	0.1369	30.803
5	0.0444	1.665	0.0740	5.550	0.0980	11.025	0.1206	18.090	0.1416	26.550	0.1614	36.315
6	0.0508	1.905	0.0847	6.353	0.1121	12.611	0.1308	19.620	0.1620	30.375	0.1847	41.558
7	0.0570	2.138	0.0950	7.125	0.1257	14.141	0.1546	23.190	0.1816	34.050	0.2071	46.598
8	0.0629	2.359	0.1048	7.860	0.1387	15.604	0.1707	25.605	0.2005	37.594	0.2286	51.435
9	0.0686	2.573	0.1144	8.580	0.1514	17.033	0.1862	27.930	0.2187	41.006	0.2494	56.115
10	0.0742	2.783	0.1236	9.270	0.1637	18.416	0.2014	30.210	0.2365	44.344	0.2696	60.660
11	0.0796	2.985	0.1327	9.953	0.1756	19.755	0.2161	32.415	0.2537	47.569	0.2893	65.093
12	0.0849	3.184	0.1415	10.613	0.1873	21.071	0.2304	34.560	0.2706	50.738	0.3085	69.413

*$\dot{Q}$'s are in cubic feet per minute (CFPM) at cavity pressure.

TABLE 3 CALCULATION OF $\dot{Q}$ FOR STREAMLINED NOSE (SN)

Run No.	Regime	L_C/D	σ_v	σ_c	V_∞ FPS	P_∞ PSIA	P_C PSIA	P_{A-S}/P_C	$\dot{Q}_{SN}$ at P_{A-S} CFPM	$\dot{Q}_{SN}$ at P_C CFPM	$\dot{Q}_{QCO}$ at P_C CFPM	$\dot{Q}_{SN}/\dot{Q}_{QCO}$ at P_C
1**	RJ	2.4	0.353	0.294	30	13.8	12.01	1.224	3.16	3.87	6.41	0.603*
2	RJ	3.1	0.328	0.273	30	13.8	12.14	1.211	5.62	6.81	7.73	0.881
3	RJ	3.7	0.311	0.259	30	13.9	12.33	1.192	7.88	9.39	8.83	1.06
4	RJ	4.1	0.302	0.252	30	13.9	12.37	1.188	9.13	10.85	9.53	1.14
5	TV	4.0	0.304	0.253	10	13.7	13.53	1.086	3.53	3.83	1.41	2.72*
6	RJ	2.3	0.358	0.294	10	13.8	13.60	1.081	0.96	1.04	0.937	1.11
7	RJ	3.1	0.328	0.273	10	13.8	13.62	1.079	2.06	2.22	1.17	1.90
8	RJ	3.4	0.319	0.266	10	13.8	13.62	1.079	2.55	2.75	1.25	2.20
9	RJ	—	—	—	—	—	—	—	—	—	—	—
10**	RJ	2.3	0.358	0.298	20	13.7	12.90	1.140	2.31	2.63	3.13	0.840*
11	RJ	3.4	0.319	0.266	20	13.8	13.08	1.124	6.67	7.50	4.18	1.79
12	RJ	4.3	0.298	0.248	20	13.8	13.13	1.120	9.32	10.44	4.97	2.10
13	RJ	3.1	0.328	0.273	40	18.0	15.06	0.976	8.55	8.34	12.68	0.658
14	RJ	3.4	0.319	0.266	40	18.0	15.13	0.972	9.37	9.11	13.58	0.671
15	RJ	3.7	0.311	0.259	40	18.2	15.41	0.954	9.64	9.20	14.47	0.636

$\sigma_v = 0.456\ (L_C/D)^{-0.292}$

$\sigma_c = 0.8333\sigma_v$

P_{A-S} = Standard atmospheric pressure = 14.7 psia

$P_C = P_\infty - \frac{1}{2}\rho V_\infty^2 \sigma_c$ = cavity pressure

$\dot{Q}_{P_C} = \dot{Q}_{P_{A-S}}\ P_{A-S}/P_C$

SN = streamlined nose

QCO = quarter caliber ogive

*These data were not included in the average value of $\dot{Q}_{SN}$

**Strut interference

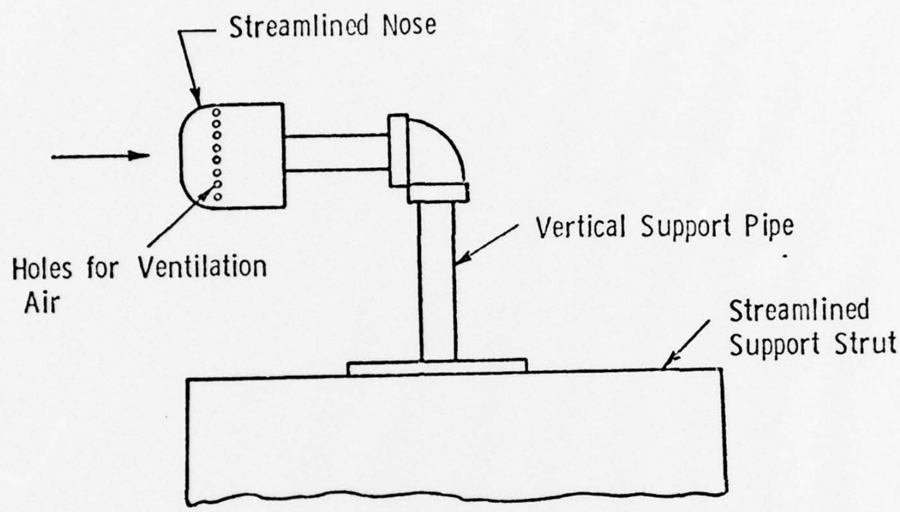


Figure 1A Initial Model Configuration

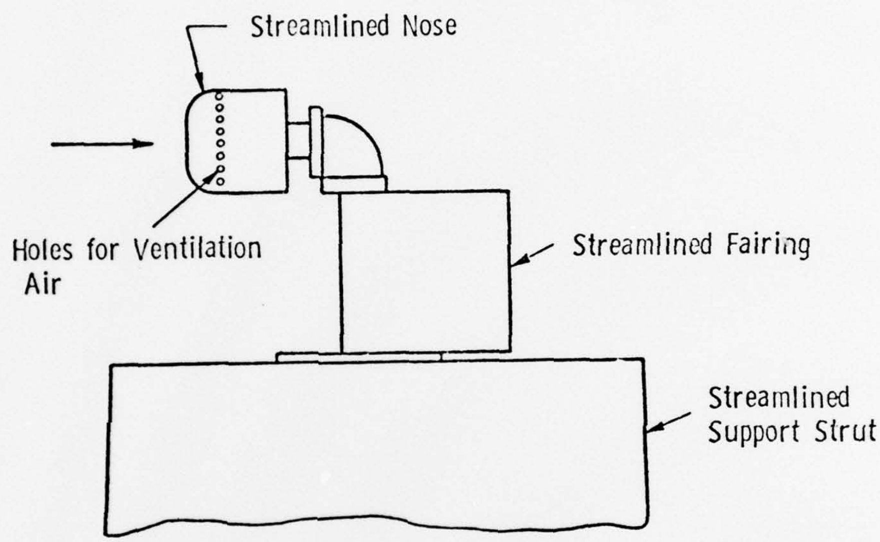


Figure 1B Final Model Configuration

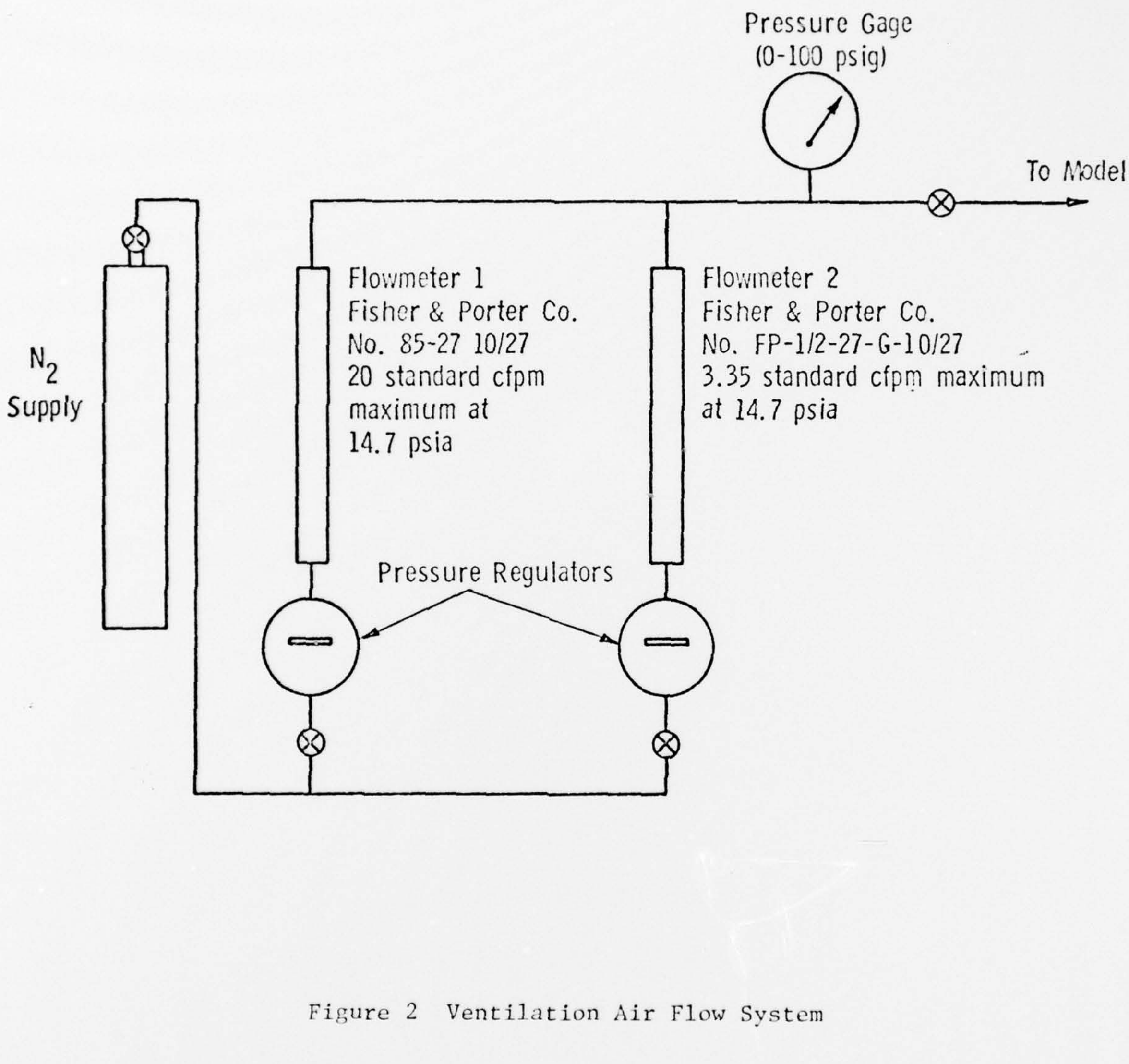
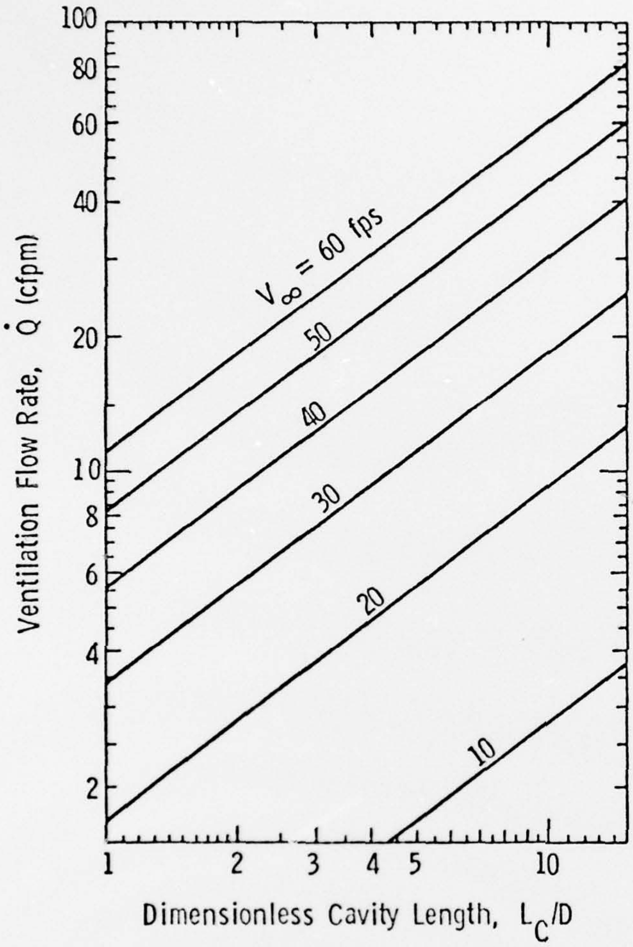
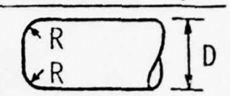


Figure 2 Ventilation Air Flow System



Quarter-Caliber Ogive



R/D = 1/4

$$C_{\dot{Q}} = 0.32 \times 10^{-4} R^{0.46} F^{0.26} \left(\frac{L_C}{D}\right)^{0.74}$$

$$R \equiv \frac{V_\infty D}{\nu}, \quad F \equiv \frac{V_\infty}{\sqrt{gD}}$$

$\dot{Q}$'s correspond to cavity pressure

Figure 3 Calculated Values of $\dot{Q}$ for a 3-inch Diameter Quarter Caliber Ogive in the Reentrant Jet Regime

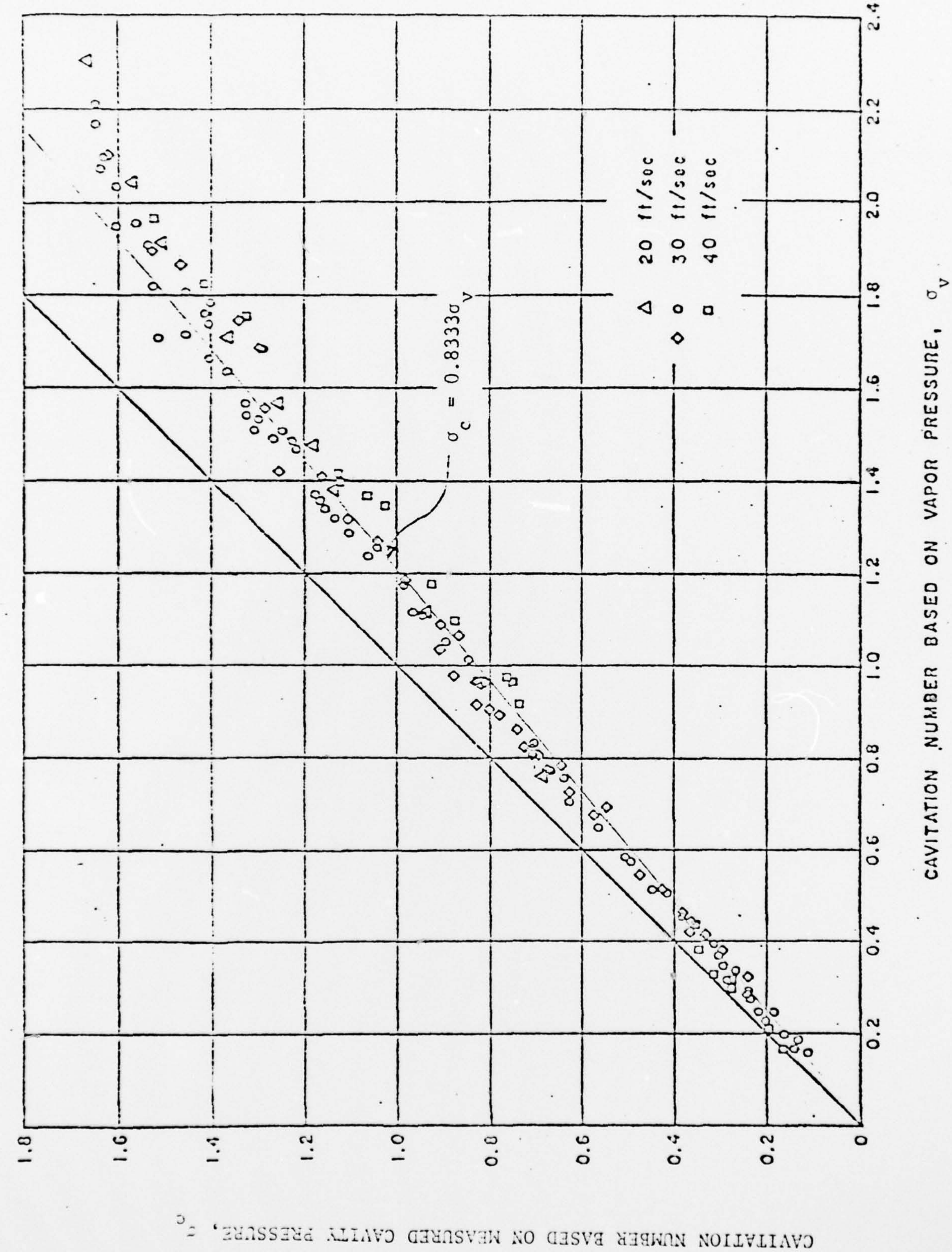


Figure 4 Comparison of σ_v and σ_c (Wade and Acosta 1966)

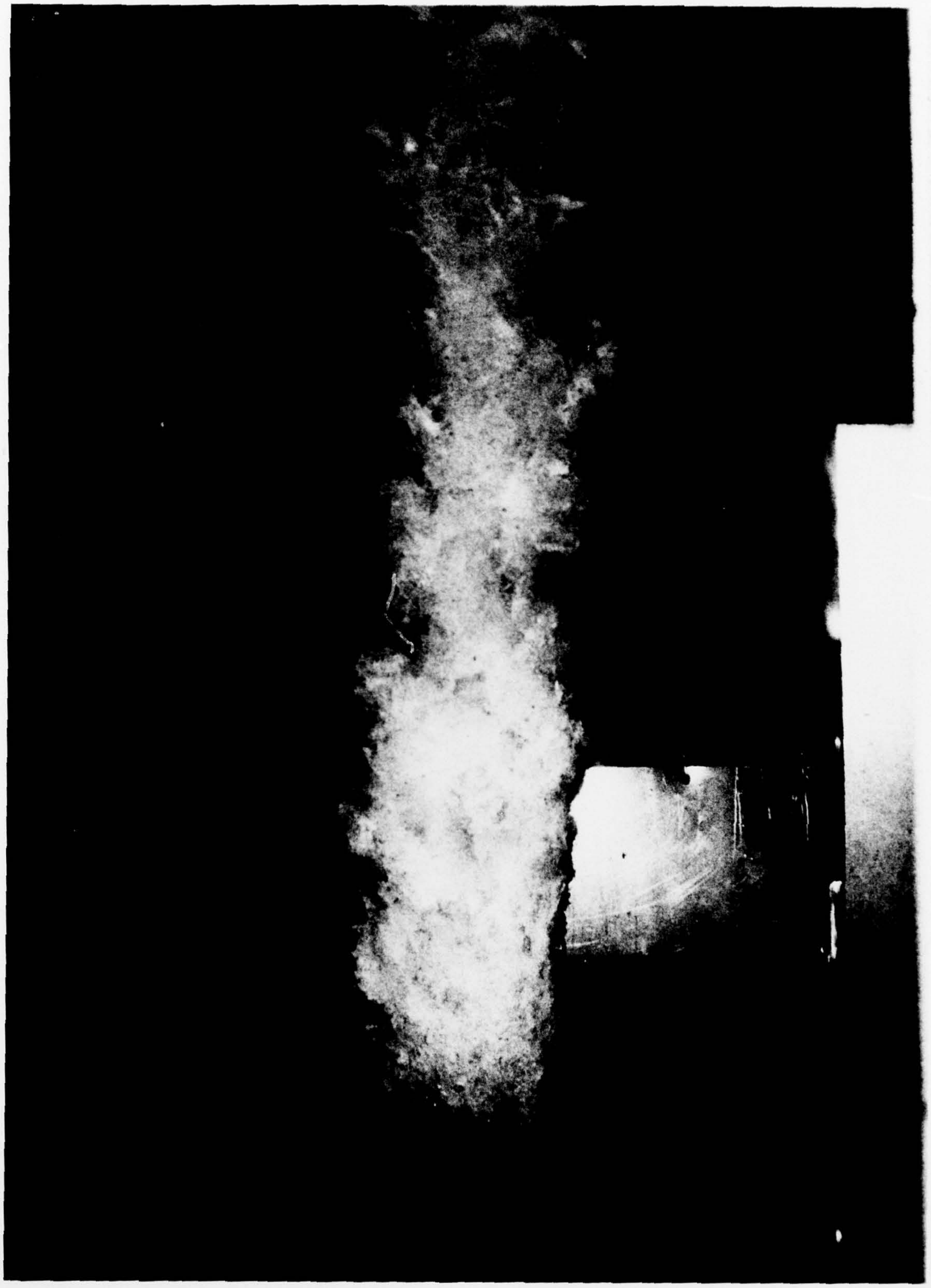


Figure 5 Reentrant Jet Regime on 3-inch Diameter Streamlined Nose
(Run 25, $V_\infty = 30$ fps, $P_\infty = 13.9$ psia)

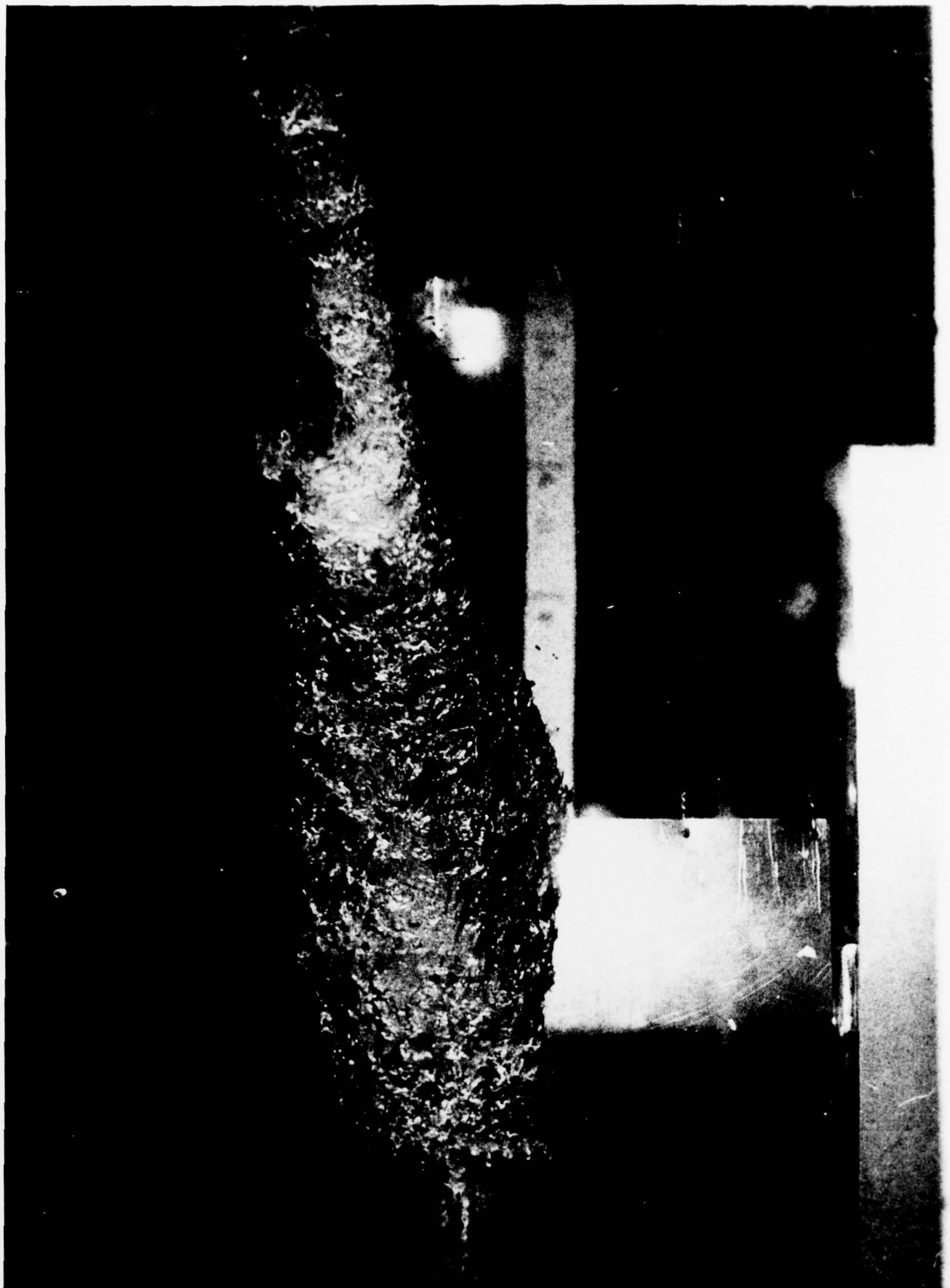


Figure 6 Twin Vortex Regime on 3-inch Diameter Streamlined Nose
(Run 23, V_∞ = 10 fps, P_∞ = 13.9 psia)

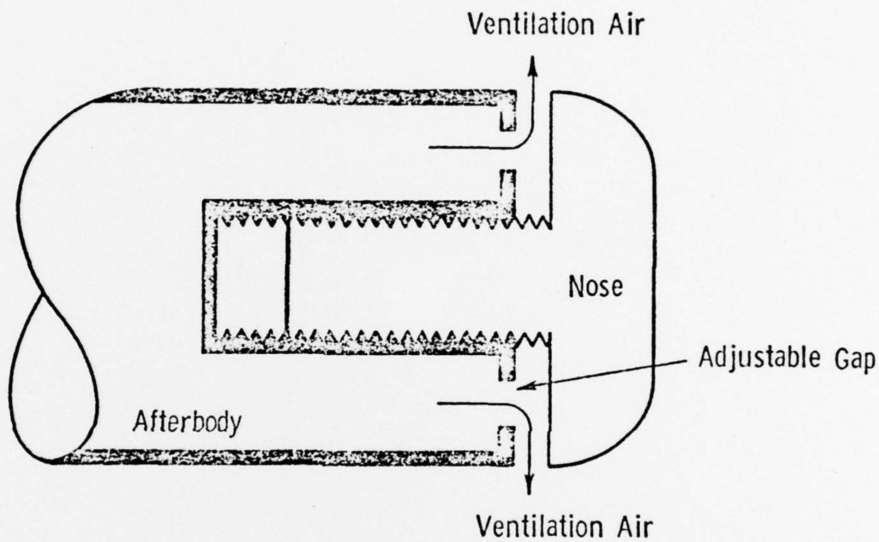


Figure 7 Proposed Model Design

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